

**STATE-OF-THE-ART PAPER**

# Clinical Utility of Computed Tomography and Magnetic Resonance Techniques for Noninvasive Coronary Angiography

Matthew J. Budoff, MD,\* Stephan Achenbach, MD,† Andre Duerinckx, MD‡

*Torrance, California; Dallas, Texas; and Erlangen, Germany*

<b>OBJECTIVES</b>	The purpose of this study was to provide a comprehensive review of the literature relating to electron beam angiography (EBA), magnetic resonance angiography, and spiral computed tomography, currently the three most promising noninvasive methods to visualize obstructions in the coronary tree.
<b>BACKGROUND</b>	Given the high costs and invasiveness of coronary angiography, there is increased interest in noninvasive coronary angiography, which has made great strides to become a clinically useful tool to augment conventional coronary angiography (CCA).
<b>METHODS</b>	MEDLINE searches were performed to include all articles related to noninvasive angiography utilizing either magnetic resonance imaging (MRI), multi-row detector spiral computed tomography (MDCT), and electron beam tomography (EBT). Weighted analysis was performed to define the published sensitivity and specificity for each technique.
<b>RESULTS</b>	Electron beam angiography (EBA) provides an overall sensitivity of 87% and specificity of 91% for the detection of obstructive coronary artery disease (CAD). Four-level MDCT data demonstrated an overall sensitivity of 59% and specificity of 89%, with higher accuracy in two recent studies of 16-level detector devices. Magnetic resonance angiography demonstrated sensitivity for detection of obstructive CAD of 77% and specificity of 71%.
<b>CONCLUSIONS</b>	Noninvasive coronary angiography is a rapidly developing technique and currently not an alternative to CCA in all cases. All three methods are currently used clinically in certain centers with appropriate expertise. Selective use should prove both cost-effective and provide a safer, less-invasive method for patients to determine the need for medical versus revascularization therapy. (J Am Coll Cardiol 2003;42:1867-78) © 2003 by the American College of Cardiology Foundation

Over the past decade, great strides have been made in cardiac imaging. The ability to visualize the lumen of the coronary artery has been at the forefront of these advances. Selective cardiac catheterization, the reference standard for visualization of coronary artery stenoses, is an invasive procedure with a significant cost and small-procedure-related morbidity and mortality. An alternative, less expensive, and noninvasive test for use as a diagnostic tool before possible intervention could have a major impact on health care practice and cost containment. Noninvasive coronary angiography, owing to rapid coronary motion, limited arterial size, and tortuous course, has been very challenging. We review here the benefits, risks, and costs of invasive angiography to that of the three noninvasive methods with the greatest clinical experience, namely electron beam tomography (EBT), multi-row-detector spiral computed tomography (MDCT), and magnetic resonance imaging (MRI).

From the \*Division of Cardiology, Saint John's Cardiovascular Research Center, Harbor-UCLA Medical Center Research and Education Institute, Torrance, California; †Department of Internal Medicine II, University of Erlangen-Nuremberg, Erlangen, Germany; and ‡Division of Radiology, University of Texas Southwestern Medical Center, Dallas, Texas.

Manuscript received February 25, 2003; revised manuscript received June 26, 2003, accepted July 1, 2003.

## ANGIOGRAPHY

Coronary angiography remains the standard for assessment of anatomic coronary disease (1). The limitations of this procedure include the risks (arterial puncture, iodinated contrast, and radiation), the need for multiple staff members including a nurse, physician, and technologists, and the costs incurred during the procedure and the ensuing observational period. Given these potential complications, the physician must make reasoned decisions on its use based on the anticipated clinical benefit versus the risks and costs of the procedure.

**Risk and utilization of invasive angiography.** The procedure is associated with a small but definable risk. The 1999 Joint Coronary Angiography Guidelines report a total risk of all major complications (including mortality) from coronary angiography to be just <2% (2). In 1993, some 1.8 million cardiac catheterization procedures were performed (3). From 1979 to 2000, the number of cardiac catheterizations increased 341%. The estimated utilization of cardiac catheterizations (inpatient and outpatient) was >2 million in the year 2000 (3).

**Costs.** The 1992 mean charge for cardiac catheterization for inpatients younger than 65 years without a diagnosis of acute myocardial infarction was \$10,880, varying by state

#### Abbreviations and Acronyms

3D	= three-dimensional
CABG	= coronary artery bypass graft
CAC	= coronary artery calcifications
CAD	= coronary artery disease
CCA	= conventional coronary angiography
CT	= computed tomography
EBA	= electron-beam angiography
EBT	= electron-beam tomography
ECG	= electrocardiographic
HR	= heart rate
MDCT	= multi-row-detector spiral computed tomography
MRA	= magnetic resonance angiography
MRI	= magnetic resonance imaging

from a low of \$6,400 in Maryland to \$17,600 in California (4). These values included all costs associated with the procedure, including ventriculography, observation, and physician charges. The physician fee made up 18% of the total, averaging \$2,000 and varying from \$1,300 in South Carolina to \$2,550 in California (5). The average total cost for patients hospitalized for diagnostic cardiac catheterization increased from \$11,232 in 1993 to \$16,838 in 2000 (6). It must be noted that there is often a large disparity between charged and collected sums; however, the costs of invasive angiography remain high. Currently, charges for noninvasive angiography range from \$1,500 to \$2,450 (including physician interpretation charges) in different medical centers. Research on the cost-effectiveness of noninvasive coronary angiography is needed before the optimal use of this procedure in a wide range of clinical circumstances can be determined.

**Current uses.** Despite cost, inconvenience, and morbidity, coronary angiography is the only method currently available for defining the details of the entire coronary endoluminal vascular anatomy, and it provides the reference standard against which other tests are compared (7). The ability to detect obstructive and nonobstructive disease is of paramount importance for guiding therapy. Although coronary lesions that reduce luminal diameter <50% are considered hemodynamically insignificant, they are not clinically benign. These lesions may progress either acutely or chronically, and patients with nonsignificant obstructions have significantly more cardiovascular events during follow-up than those with truly normal coronary angiograms (8). Furthermore, cardiac angiography can also define multiple cardiac diseases (cardiomyopathy, heart failure, valve disease, and endothelial dysfunction).

**Potential role of noninvasive angiogram.** Although conventional coronary angiography (CCA) remains the standard of reference for determining the severity of stenosis resulting from atherosclerosis in the coronary arteries, it is unfortunate that at least 20% of the clinically indicated diagnostic CCA procedures performed each year reveal no evidence of obstructive coronary artery disease (CAD), and

therefore do not lead to further interventional procedures (9). This problem may be twice as significant in women. A recent report of 9,238 angiograms from five community hospitals demonstrated that 40.4% of women referred for angiography were found to have nonsignificant disease, nearly twice that of men (10). Because most of the risk of conventional angiography including stroke, MI, infection, and bleeding, revolves around the need for arterial access, noninvasive methods, approached by intravenous administration of contrast (or no contrast at all), eliminate most of the risk associated with the procedure, including postprocedural observation periods, MI, stroke, bleeding, arterial infection, and vessel dissection.

**Difficulties of noninvasive angiography.** Fluoroscopy, the method used to visualize the coronary artery lumen during angiography, has high temporal resolution, but low contrast resolution. Thus, it requires direct enhancement of the coronary artery blood pool to allow visualization of the lumen. Noninvasive angiography, without direct injection of contrast into the artery, utilizes increased spatial resolution to overcome the problems of loss of superb contrast enhancement and temporal resolution. Furthermore, rapid motion of the coronary arteries, complex and tortuous anatomy, as well as the small size of the vessels, all make noninvasive imaging challenging. All three techniques rely upon three-dimensional (3D) reconstruction to assist with visualization. The computed tomography (CT) techniques (EBT and MDCT) rely upon superior spatial resolution and a venous contrast injection. The venous contrast does not provide as robust an enhancement of the coronary arteries as does direct arterial injection, because the contrast is diluted by mixing with the blood pool. Magnetic resonance imaging often utilizes gadolinium, a noniodinated contrast agent, to increase the identification of the lumen.

## ELECTRON BEAM TOMOGRAPHY

Electron beam tomography with electrocardiographic (ECG) triggering has been used for detecting and quantifying coronary artery calcifications (CAC) for more than 15 years (11,12); EBT is established as the "gold standard" for CAC detection (13). Though CAC scores correlate well with the total atherosclerotic burden (14,15) and strongly predict future cardiac events (16,17), the amount of CAC does not correlate well with the stenosis severity of a given lesion (18). Although high calcium scores impart an approximate 10-fold increased risk, they do not always impart a tight stenosis (Table 1) (19). Moreover, because plaque burden itself is dangerous regardless of stenosis severity, use of calcium scanning for predicting the need for angioplasty or bypass surgery is limited.

Electron beam tomography appears well suited for imaging of the coronary artery. It has a unique combination of high temporal resolution (100 ms/slice) and spatial resolutions ( $0.35 \times 0.35 \times 1.5$  mm) (13), allowing visualization of small lesions. Furthermore, ECG triggering allows image

**Table 1.** Characteristics and Risk Ratio for Follow-Up Studies Using Electron Beam Tomography (Modified From Budoff [19])

Investigator	No.	Mean Age (yrs)	Follow-Up Duration (yrs)	Gender (% Male)	Calcium Score Cutoff	Risk Ratio
Georgiou	192	53	4.2	54	Median†	13.1
Detrano	491	57	2.5	64	Top quartile	10.8
Keelan	288	56	6.9	77	Median (>480)	3.2
Arad	1,173	53	3.6	71	CAC >160	20.2
Agatston	367	52	6.0	68	CAC >50	16.9
Detrano	1,196	66	3.4	89	CAC >44	2.3
Park (subset of Detrano)	967	67	6.4	91	CAC >142.1	4.9
Raggi	632	52	2.7	51	Top quintile*	15.4
Wong	926	54	3.3	79	>270-top quartile	8.8
Arad	5,585	59	4.3	70	CAC ≥100	10.7
Kondos	5,635	51	3.1	74	CAC present	men 10.5, women 2.6

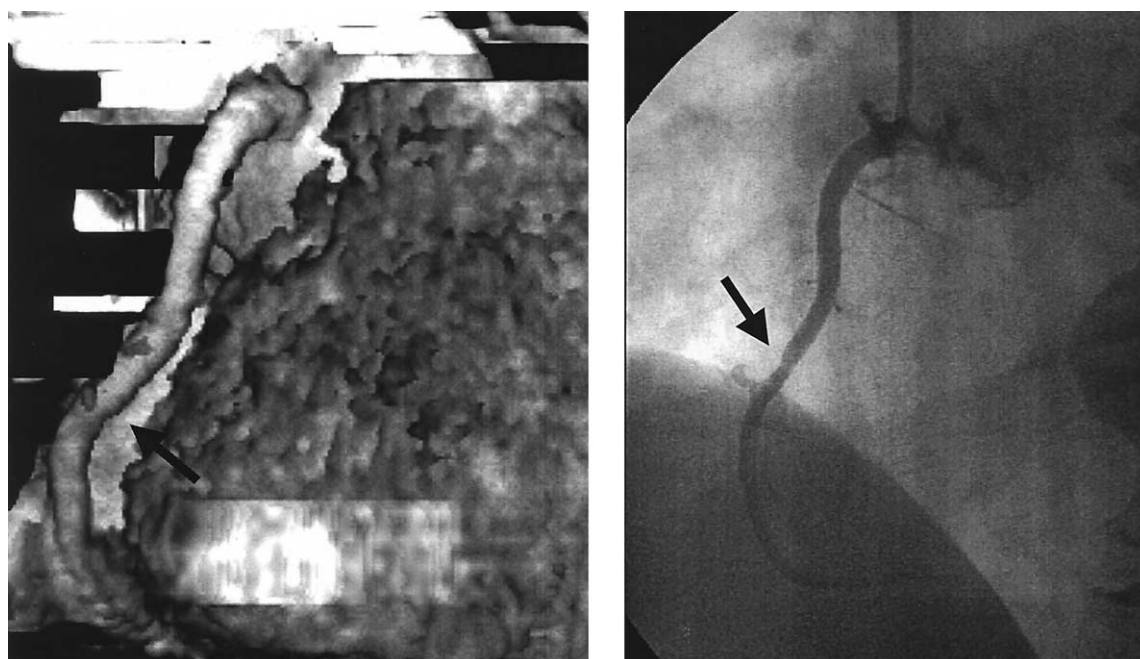
\*Using age- and gender-matched cohorts, representing the top quintile; †using age- and gender-matched cohorts, representing top quartile.  
CAC = Coronary Artery Calcium Score.

acquisition during the slow portion of coronary motion (diastole) (20,21). Contrast-enhanced electron beam angiography (EBA) is an emerging technology with the potential for obtaining essentially noninvasive coronary arteriograms (Figs. 1 and 2). Recent studies have reported contrast-enhanced, ECG-triggered, 3D EBA for detecting and grading coronary stenosis (22-28).

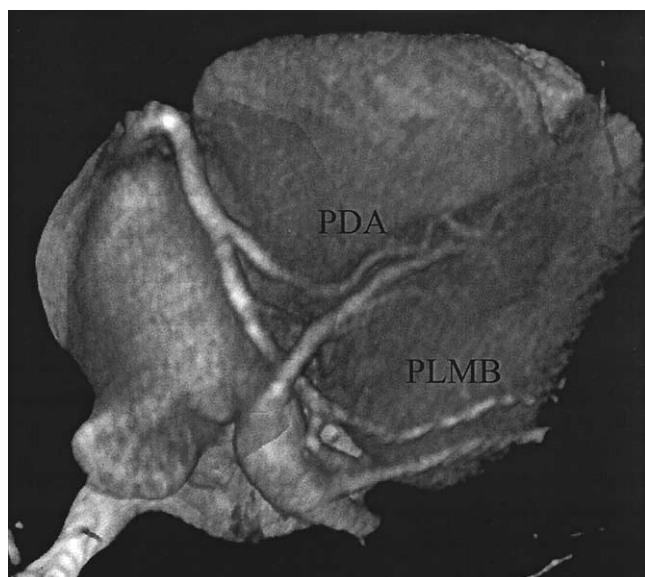
Coronary artery EBA, a noninvasive diagnostic procedure for demonstrating coronary artery anatomy, was first introduced in 1995 (22). Two studies (28,29) confirmed that coronary EBA with 3D techniques could reveal the lumen of long segments of the major coronary arteries with high correlation to conventional selective CCA ( $r = 0.83$ ) (29). In evaluating this modality, comparison to CCA was performed so as to assess the accuracy in which it can detect a significant stenosis (>50% luminal diameter). This mo-

dality has been demonstrated to identify significant coronary lumen narrowing (>50% stenosis) with the sensitivity of 74% to 92%, specificity of 79% to 100%, and accuracy of 81.2% to 93.4% (Table 2). Summary data demonstrate an overall sensitivity of 87% and specificity of 91% for the 583 patients reported in these studies. The EBT noninvasive angiography had a success rate of 70% to 93% in the ability to correctly interpret all three coronary arteries per patient (26-28). Also, interobserver reproducibility was found to be high (0.74 to 0.90 by Cohen's kappa statistic) (26,27).

There is fair uniformity and imaging standards among EBA studies. The imaging procedure used by the above studies are all performed with similar imaging techniques. The studies were performed with a C-100 or C-150XLP electron beam CT scanner (Imatron, South San Francisco, California). The ECG triggering is employed so that each



**Figure 1.** Electron-beam angiogram (left) and corresponding invasive angiograms (right) of a person referred to the cardiac catheterization laboratory for evaluation of chest pain. The three-dimensional reconstruction and corresponding angiograms revealed no significant obstructive disease, but did reveal 20% to 30% stenosis of right coronary artery in the midvessel (black arrow).



**Figure 2.** Electron-beam angiogram of the distal coronary arteries. Although the distal right coronary can only be visualized 80% of the time by this technique, this image demonstrates the posterolateral marginal branch (PLMB) and posterior descending arteries (PDA). Image courtesy of Dr. Beh, Kuala Lumpur, Malaysia.

image is obtained at the same point in diastole. Iodinated contrast is administered through an antecubital or jugular vein with an injection rate of 4 ml/s and total volume of 120 to 160 ml. Forty to 50 images are obtained over a single breath-hold, usually over 25 to 40 s. This entire protocol is performed within 15 min. The test is easy to perform, and interpretation can be made in minutes.

**Limitations of EBT.** The EBA studies had a technical success rate of 85% to 100%, and 8% to 25% of coronary arteries were nonassessable (Table 2). Impaired image quality, due to multiple image artifacts including coronary artery motion and breathing artifacts, limited EBA clinical use. One major limitation of all noninvasive imaging is dense calcifications in the coronary tree, with investigators citing scores  $>500$  or  $>1,000$  as problematic (26,27). Because the calcification score is not always known in advance of noninvasive angiography, some cases will prove nondiag-

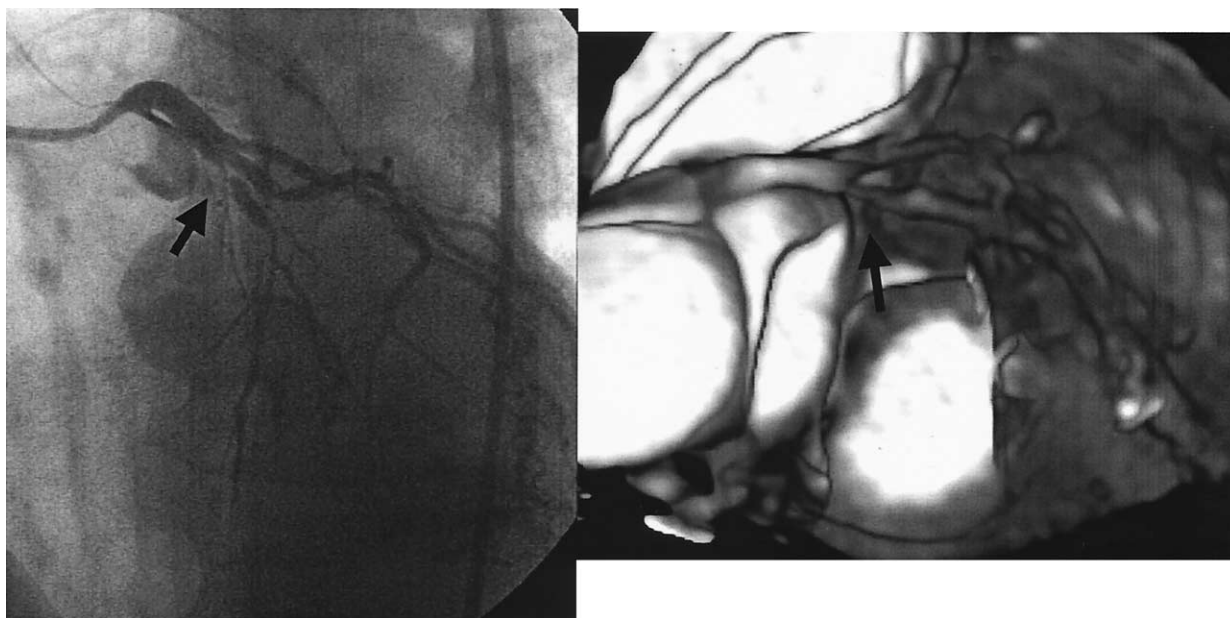
nostic. In EBA studies, distal arteries are not as well visualized as the proximal segments. This is most likely due to the greater motion artifacts from cardiac pulsation and the partial volume effect (due to small vessel diameters) in distal epicardial vessels, as compared with the proximal segments (24,26,30). Another limitation of all noninvasive angiography is the relative inability to visualize collaterals. The main determinant of false positive results for diagnosing  $\geq 50\%$  coronary luminal stenosis was small vessel size (22,30), and the diameter of stenotic segments tends to be underestimated by EBA (24).

Some progress has been made over the last year to improve image quality and interpretation of the EBA. Recent studies revealed that the ECG triggering at 80% of the R-R interval (late diastole) used in most earlier studies might not be optimal for imaging of the coronary segments near the right or left atria, because atrial contraction during end-diastole causes rapid movement of the base of the heart (26,31). It has been recently demonstrated that there is less coronary motion at 40% of the R-R interval (early diastole or end-systole) (32,33), which might significantly improve imaging. Improvements including more reliable ECG gating, use of different ECG triggers (40% instead of 80% of the R-R interval), and greater experience with this technique will continue to improve accuracy. Hardware improvements in the EBT scanner should also lead to higher accuracy. An available high-resolution detector system improves the spatial resolution by almost 40%, thus enabling improved imaging performance for future studies (34). Furthermore, the new e-speed scanner (GE-Imatron, South San Francisco, California) allows for image acquisition in 50 ms, as well as obtaining dual imaging and allowing for thinner slices with less cardiac motion. Currently, the high negative predictive values (95% to 98%) have demonstrated the ability of this tool to effectively "rule out" the presence of obstructive CAD, thus helping the clinician to potentially utilize this tool to determine the need for medical versus revascularization therapy.

**Electron beam angiography after revascularization.** The EBA is a promising tool in the follow-up after coronary interventions, with the potential to replace some invasive catheterization procedures (Figs. 3 to 5) (35). The utilization of EBA to detect the patency of coronary artery bypass graft (CABG) has been reported as early as 1986 (36). Saphenous vein grafts, which are generally of large caliber and have little cardiac motion, are especially well suited for noninvasive imaging with EBA (Figs. 4 and 5). Flow studies (sequential image acquisition to determine the rate of contrast enhancement at a particular point in the anatomy) demonstrate graft patency with sensitivities of 93% to 96% and specificities of 86% to 100% (35,37-40). Using 3D visualization in patients post-CABG, graft stenosis and patency can be determined. Recent studies demonstrated a sensitivity of 92% to 100% and specificity of 91% to 100% for establishing patency (and lack of significant obstructive disease) of saphenous vein grafts as compared with CCA

**Table 2.** Comparisons of Contrast-Enhanced Electron Beam Computed Tomography and Invasive Coronary Angiography

Investigator (Ref)	Patients	Sensitivity (%)	Specificity (%)	Unevaluable (%)
Achenbach (27)	125	92	94	25
Budoff (26)	52	78	91	11
Moshage (22)	20	74	100	—
Reddy (25)	23	88	79	8
Rensing (30)	37	77	94	19
Schmermund (31)	28	83	91	12
Nakanishi (111)	37	74	94	12
Moshage (100)	118	90	82	24
Achenbach (112)	36	92	91	20
Lu (113)	107	91	93	7
Summary	583	87	91	16

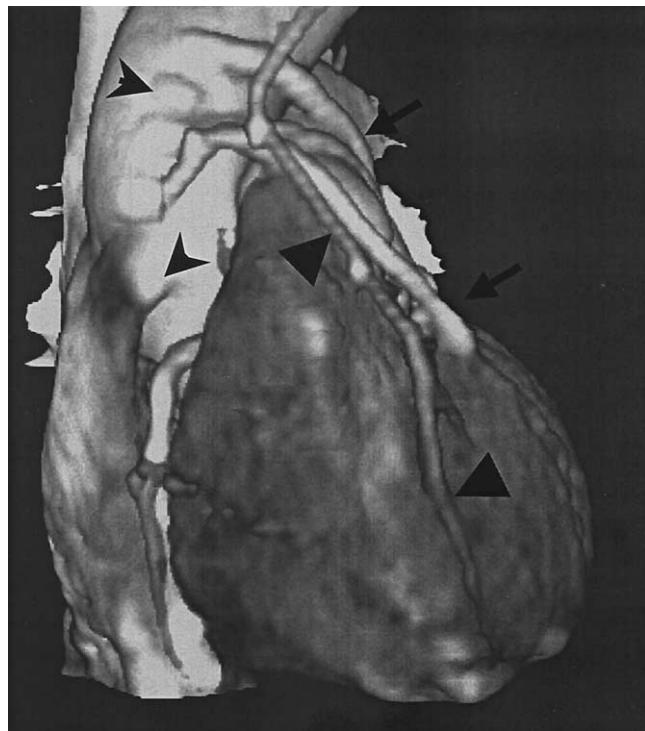


**Figure 3.** Electron-beam angiogram taken after symptoms of chest discomfort status postpercutaneous coronary angioplasty of the proximal left anterior descending. The image reveals a restenosis (**black arrows**) of the left anterior artery on both noninvasive and invasive angiograms.

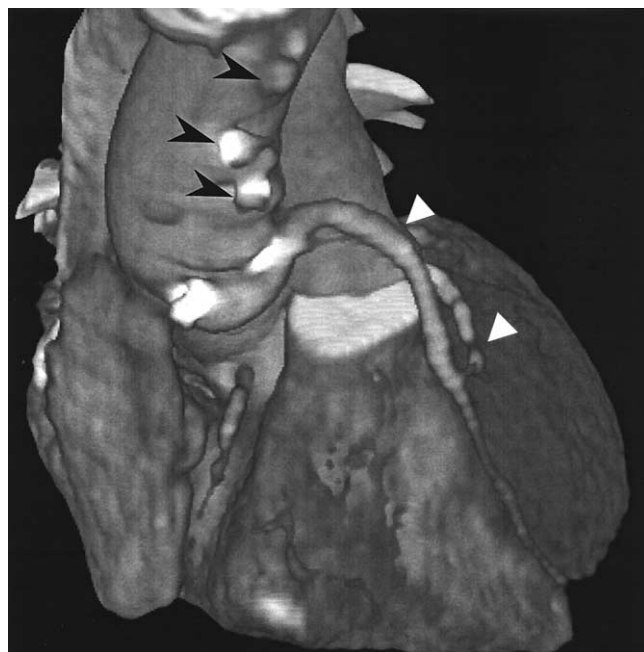
(35,41,42). The same studies demonstrated sensitivity and specificity for patency of left internal mammary of 80% to 100% and 82% to 100%, respectively. Studies by Achenbach et al. (35) and Ha et al. (41) demonstrated that significant

stenoses can be determined by EBT in the grafts, similar to those assessed in the native coronary arteries.

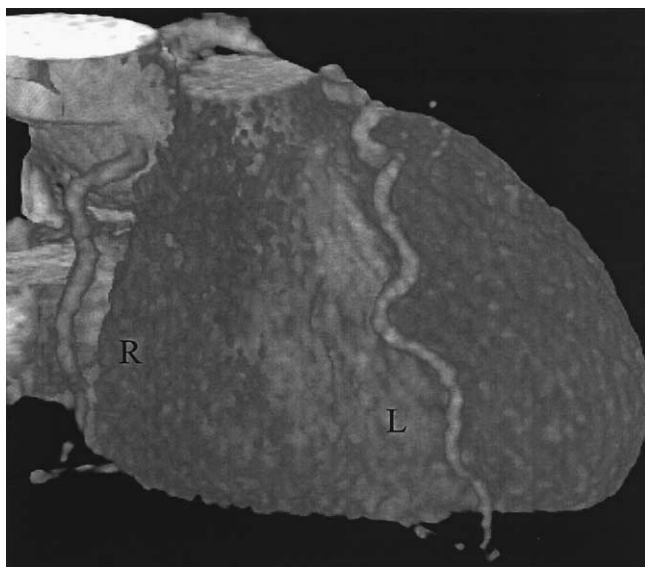
Percutaneous transluminal coronary angioplasty procedures are performed worldwide as one of the main methods for coronary artery stenosis treatment (43). However, even with intracoronary stents, restenosis (closure) of the site of angioplasty is still the greatest risk, which can lead to both



**Figure 4.** Electron-beam angiogram of a person eight years' postcoronary bypass surgery. The left internal mammary graft is widely patent, inserting into the left anterior descending artery (**black triangles**). The distal artery is well seen and patent, with minimal distal disease. There are two closed saphenous vein grafts (**black arrowheads**), in addition to two patent saphenous vein grafts, one to a diagonal and one to an obtuse marginal. The right coronary artery has a 100% midvessel stenosis (**black arrows**).



**Figure 5.** Electron-beam angiogram of a person 22 years after coronary bypass surgery. A saphenous vein graft is widely patent, inserting into the left anterior descending artery, just after a high-grade stenosis in the native coronary (**white triangles**). The distal artery is well seen and patent, extending around the apex of the heart. Three saphenous vein grafts are closed proximally (**black arrowheads**).



**Figure 6.** Multislice computed tomography angiogram (four-detector) of the left anterior descending (L) and right coronary artery (R).

MI and death. Chest pain after stenting or angioplasty often requires visualization of the site of angioplasty to assess for early closure. A noninvasive method to visualize the site of angioplasty could potentially be used for less typical presentations of acute closure (no typical angina or ECG changes suggestive of ischemia). Use of EBA has been shown to permit imaging of the coronary arteries and detection of high-grade restenosis after coronary angioplasty (Fig. 3). Achenbach et al. (44) reported 50 cases in which coronary angioplasty was performed without coronary stent implantation. The sensitivity and specificity of EBA was 94% and 82%, respectively, to detect severe stenosis ( $\geq 70\%$  stenosis).

Intracoronary stenting is now increasingly used to decrease the restenosis rate of coronary angioplasty (45) and to avoid emergent complications, such as acute thrombus, coronary artery dissection, and even emergent CABG (46). The ability to visualize the coronary lumen through the metal of the stent poses severe problems for EBA, MDCT, and magnetic resonance angiography (MRA). The widespread utilization of metal stents during revascularization procedures provides a major limitation for the clinical application of these techniques. One potential solution to the problem of visualizing the lumen within the stented region is to utilize EBA flow studies to evaluate contrast enhancement distal to the stent for patency (47–50). Pump et al. (50) reported a sensitivity of 78% (18 of 23 stenoses detected) and specificity of 98% (189 of 193 stents correctly judged to be free of stenosis) for the detection of significant in-stent restenosis by EBA flow measurements.

**Current clinical uses.** The most common clinical application of EBA is to evaluate patients with symptoms post-CABG surgery and coronary angioplasty evaluation, assessment of congenital heart disease and coronary anomalies (51), and measurement of wall motion, myocardial mass,

and right and left ejection fractions (52,53). Given the high negative predictive values, use in patients with lower probabilities of obstructive disease will potentially allow physicians to exclude obstructive CAD in proximal and midvessels. As compared with CCA, use of EBA is minimally invasive, has an extremely short acquisition time, and was a markedly lower radiation dose (54). Patients unable to breath-hold for 25 s, those with significant arrhythmias, and morbidly obese patients are poor candidates for EBA. The Food and Drug Administration has approved EBT for use in noninvasive coronary angiography. The newest model of EBT is the e-speed scanner, allowing for 50-ms image acquisition and multidetector imaging. This new device, currently available only in limited centers, will shorten breath-hold, lower radiation, and decrease motion artifacts owing to faster image acquisition.

## SPIRAL COMPUTED TOMOGRAPHY

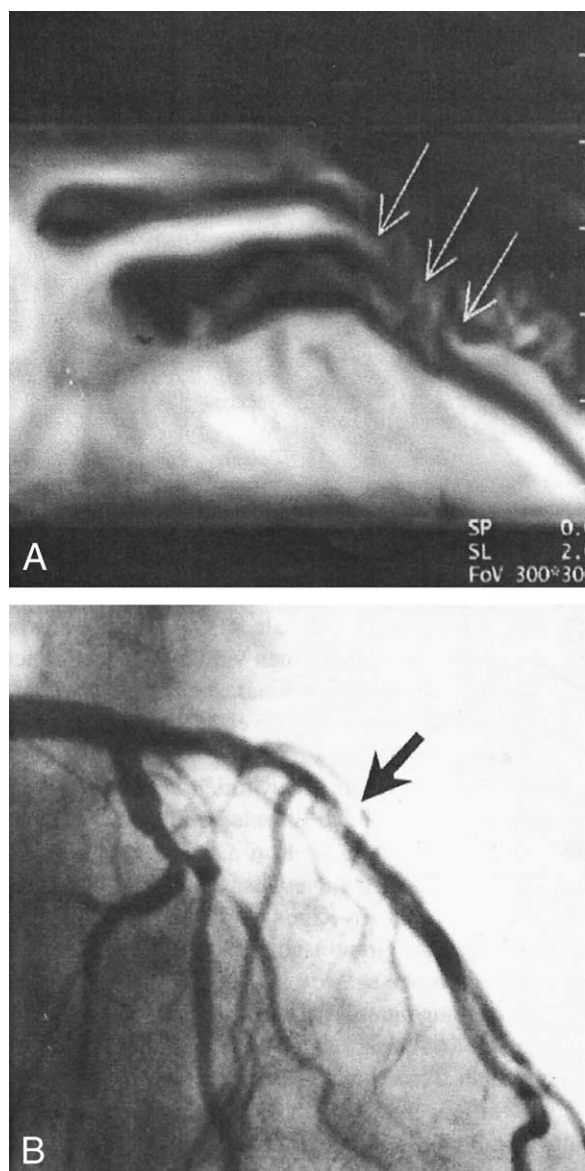
The “need for speed” is essential in obtaining virtually motion-free images. The significantly improved temporal and spatial resolution of MDCT scanners opens up new possibilities for cardiac imaging. Because of high in-plane resolution and thin-slice collimation (up to 1.0 mm), high-quality images can be obtained (Fig. 6). However, as the mechanical detector head must rotate around the patient, no current CT can obtain a full rotation in less than 400 ms, too slow to allow for motion-free imaging of the coronary arteries (55,56). Multislice CT has the new capability of obtaining multiple images simultaneously, continuously imaging, obtaining 4, 8, or even 16 slices at once. Each slice is still obtained with the limited gantry rotation speed, but simultaneous imaging allows for thinner slices and shorter scanning protocols (decreased need for long breath-holding by patient). The newer MDCT equipment now rotates at 420 ms, with up to 16 detectors for cardiac imaging.

Through the use of simultaneously recorded ECG data, images from the MDCT can be reconstructed at any point

**Table 3.** Comparisons of Contrast-Enhanced Four-Level Multirow Detector Spiral Computed Tomography and Invasive Coronary Angiography

Investigator (Ref)	Patients	Sensitivity (%)	Specificity (%)	Unevaluable (%)
Achenbach (59)	64	85	76	32
Knez (58)	44	58	91	30
Hong (114)	25	80	76	
Giesler (115)	83	56	86	29
Giesler (60)	100	49	89	29
Nieman (61)	53	61	93	30
Nieman (62)	78	63	94	32
Kuettner (63)	66	37	99	31
Summary	513	59	89	31





**Figure 7.** Navigator-echo-based, noncontrast-enhanced magnetic resonance coronary angiography (A) in a patient with a stenosis of the left anterior descending coronary artery (arrows). (B) Corresponding invasive coronary angiogram of that patient.

in the cardiac cycle. The MDCT obtains continuous volume imaging of the heart (up to 400 images of the coronary tree are obtained), then utilizes a fraction of the obtained data for image reconstruction. Retrospective triggering, acquiring partial data on each scan, may allow shorter acquisition times, but require sophisticated postprocessing algorithms to reduce motion artifacts (56). Several studies are listed in Table 3. Achenbach et al. (57) reported the applicability and image quality of MDCT and EBT on 30 patients without coronary stenoses. This demonstrated that coronary arteries could be visualized over long segments. On average, 73% of the proximal and midsegments could be visualized free of motion artifacts with MDCT (92% with EBT,  $p < 0.001$ ),

and coronary diameters showed close correlation with both techniques to quantitative coronary angiography ( $r = 0.86$ ).

Multiple studies with four-slice MDCT have been reported. Most studies reported a diminished overall sensitivity. One MDCT study demonstrated an overall sensitivity of 58%, which varied widely from vessel to vessel (58). The left main coronary artery had a sensitivity of 100%, whereas stenoses in the circumflex had a sensitivity of only 44%. Most studies demonstrate approximately 70% of vessels available for analysis (Table 2). Another study had 68% of vessels interpretable, and 32 of 58 high-grade stenoses were detected (sensitivity 58%) (59). However, all four major coronary arteries could be evaluated in only 30% of patients. The investigators note that "its clinical use may presently be limited due to degraded image quality in a substantial number of cases, mainly due to rapid coronary motion." Giesler et al. (60) reported 115 of 400 (29%) coronary arteries uninterpretable, and in only 39% of patients were all coronary arteries assessable by MDCT. Overall, 51 (49%) of 104 stenoses were revealed on MDCT. Most studies demonstrate a significant heart rate (HR) interaction. One study showed that overall sensitivity for stenosis detection decreased from 62% (HR <70 beats/min) to 33% (HR >70 beats/min) (60), whereas sensitivity dropped in another study from 82% (mean HR 55.8 beats/min) to 32% (mean HR 81.7 beats/min) (61,62). In another study (63), the correct clinical diagnosis could be obtained in only 36% of patients (Table 3).

**Limitations of MDCT.** Because radiation is continuously applied while only a fraction of the acquired data is utilized, high radiation doses (doses of 6 to 10 mSv/study) limit the clinical applicability of this modality (54,64). In female patients, the effective radiation dose is another 25% higher than in male patients (WinDose 2.0a, Scanditronix Wellhofer, Bartlett, Tennessee), raising the mean dose from 8 mSv in men to 10 mSv per study in women (65). These radiation doses are two to five times higher than can be expected for conventional angiography, and 5- to 10-fold higher than doses obtained during EBA (1 to 1.7 mSv) (2,64,67). In two studies of radiation dose, EBA yielded doses of 1.5 to 2.0 mSv, MDCT angiography 8.1 to 13 mSv, and coronary angiography 2.1 to 2.3 mSv (66), whereas another study reported EBA doses of 1.1 mSv and MDCT doses of 9.3 to 11.3 mSv (67). The radiation dose using the new 16-level detectors has not yet been reported.

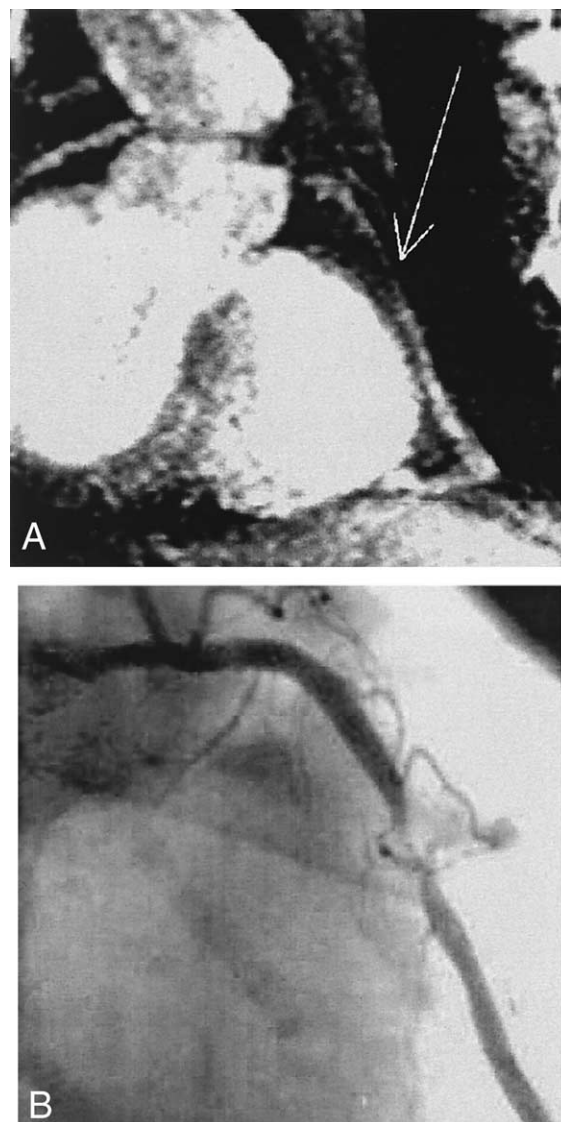
**Current clinical uses.** The use of the new 16-slice MDCT scanners (420-ms rotation time,  $12 \times 0.75$  mm collimation) allows for faster and thinner imaging than the four-slice scanners. Two studies have been reported, each with improved accuracy as compared with prior reports with four-slice scanners. These studies reported sensitivity of 73% to 95% and specificity of 86% to 93% (68,69). Both studies concluded the MDCT with beta-blocker premedication permits detection of CAD with high accuracy. Reduced radiation doses and improved rotation times will make MDCT a more clinically useful modality.



**Figure 8.** Three-dimensional surface reconstruction of normal coronary arteries obtained by navigator-echo-based three-dimensional magnetic resonance coronary angiography.

**Magnetic resonance angiography.** The MRA provides excellent soft tissue contrast, has inherent 3D capabilities, and allows acquisition in any anatomic plane. Furthermore, MRA does not expose the patient to radiation, nor iodinated contrast, making this the safest of the current noninvasive modalities, excluding those patients with pacemakers, implantable defibrillators, or recent stent placement. An MRA of the coronary arteries became possible in 1991 with the development of a new group of fast magnetic resonance imaging (MRI) sequences (70,71). The new MRI techniques may also allow quantification of velocity and flow in coronary arteries; also, MRI has proved successful in producing angiograms of peripheral vascular anatomy and abnormalities (72). Recent advances in fast magnetic resonance imaging (MRI) have allowed for compensation of coronary and respiratory motion (73-76). However, limitations in spatial and temporal resolution make visualizing coronary artery lumens more difficult (Fig. 7-9).

All coronary MRA techniques use ECG-triggering. First-generation breath-hold techniques acquire one two-dimensional image per breath-hold; however, the clinical usefulness was severely limited (77-82). The second-generation techniques use respiratory gating or triggering and are referred to as "non-breath-holding" or "free-breathing" techniques, as they do not require breath-holding during image acquisition (83,84). Third-generation techniques that allow 3D volume acquisitions in a single breath-hold, in combination with real-time interactive slice positioning, appear very promising. Real-time slice positioning, and higher-resolution acquisition schemes, such as spiral MRA, can further improve and facilitate the use of these coronary MRA techniques (85-96) (Figs. 7 and 8). The newest versions will allow 3D volume acquisitions in one breath-hold and/or real-time interactive slice positioning (Fig. 9) (97-101). In addition, the use of magnetic



**Figure 9.** Magnetic resonance coronary angiogram of the right coronary artery obtained in a single breath-hold. A stenosis of the right coronary artery can be seen (arrow, A). (B) Corresponding invasive coronary angiogram also demonstrates the stenosis.

resonance contrast agents appears to further improve some techniques (102,103).

**TWO-DIMENSIONAL MAGNETIC RESONANCE CORONARY ANGIOGRAPHY (FIRST- AND SECOND-GENERATION TECHNIQUES).** The breath-hold two-dimensional technique represented the first attempt at high-resolution imaging of the coronary arteries (77). A breath-hold lasting 16 heartbeats could produce a single image (Table 4). However, multiple breath-holds were necessary to cover all parts of the coronary artery tree, and the exact reproduction of the level of inspiration required extremely good collaboration of the patient and caused problems in up to 44% of all subjects. Other limitations of the technique included long study times, difficulties in distinguishing veins or pericardial structures from coronary arteries, poor visualization of the left main coronary artery, and impaired image quality due to



**Table 4.** Sensitivity and Specificity for the Detection of Coronary Artery Stenoses by Two-Dimensional Breath-Hold (First Generation) Magnetic Resonance Coronary Angiography in Comparison With Conventional Invasive Coronary Angiography

Investigator (Ref)	Patients	Sensitivity (%)	Specificity (%)	Spatial Resolution (mm)	Temporal Resolution (ms)
Manning (78)	39	90	92	$1.4 \times 0.9 \times 5.0$	80–104
Pennell (80)	39	85	–	$1.6 \times 0.8 \times 5.0$	126
Post (81)	35	40–63	89–97	$1.8 \times 1.0 \times 4.0$	88–113
Mohiaddin (82)	16	56	82	$1.6 \times 0.8 \times 4.0$	126
Duerinckx (73)	21	63	–	$1.0 \times 2.0 \times 5.0$	117

ghosting, ringing, and blurring (79). Although an early study with MRA yielded favorable results (78), multiple subsequent studies could not reproduce the promising results obtained in these initial reports (73,79–82) (Table 4).

**THE 3D RESPIRATORY GATED MAGNETIC RESONANCE CORONARY ANGIOGRAPHY TECHNIQUES (THIRD-GENERATION TECHNIQUES).** A number of clinical studies have compared the results obtained by these 3D respiratory-gated MR coronary angiography techniques to conventional invasive coronary angiography (Figs. 7 and 8) (90–93). Accuracy varies widely from study to study (sensitivity: 38% to 83%, specificity: 57% to 95%) even when the exams of subjects with poor image quality are excluded (Table 4). A recent multicenter study of 109 patients using the free-breathing technique revealed a total of 636 of 759 proximal and middle segments of coronary arteries (84%) were interpretable on MRA (104). In these segments, 78 (83%) of 94 clinically significant lesions (those with a >50% reduction) were detected by MRA. Overall, coronary MRA had an accuracy of 72% (95% confidence interval, 63% to 81%) in diagnosing CAD (104). Summary data reveal a sensitivity of 77% and specificity of 71% in the 387 patients reported in these studies.

**Study limitations.** The combination of temporal and spatial resolution currently available with MRA is limited. For MRA, the spatial resolution is inversely proportional to the temporal resolution. Currently used protocols use temporal resolution of approximately 125 ms, and spatial resolution of  $1.2 \times 1.2 \times 2.0$  mm (Table 5). Other limitations are due to calcifications, metal artifacts, thickened pericardium, and

pericardial fluid collections, as well as a mean study time of 70 min (42,104). Finally, patients with claustrophobia, recently implanted stents or other metallic objects, pacemakers, or implantable defibrillators cannot undergo this procedure.

**RECENT DEVELOPMENTS.** To overcome the difficulties associated even with 3D navigator-echo-based image acquisition techniques for coronary MRA, a number of new imaging protocols have been developed. Major aim of these approaches was to increase the signal-to-noise ratio of the coronary artery through the injection of contrast agent (Fig. 8) (99,101–106). By use of flow modes and 3D reconstruction, MRI can also visualize CABG patency with high accuracy. Studies demonstrate a diagnostic sensitivity of 93% to 98% and specificity of 85% to 97% for saphenous vein grafts (107,108).

**Clinical applications.** Although the role of coronary artery MRA for stenosis detection has not yet been established, coronary MRA has already been very successful in the detection of coronary artery variants, and the imaging of coronary stents and bypass grafts (109,110). Spatial and temporal resolution are constantly improving and, in selected cases under nonclinical conditions, MR even permits imaging of the coronary vessel wall (75). Multiple new techniques (including new coils, contrast agents, and acquisition methodology) are currently being developed and should continue to improve upon the current state.

**Conclusions.** Electron beam angiography (111–113), MDCT (68,114,115), and MRI coronary angiography (116,117) are rapidly developing techniques and currently

**Table 5.** Detection of Coronary Artery Stenoses: Comparison of the Sensitivity and Specificity (>50% Stenosis) of Third-Generation Magnetic Resonance Coronary Angiography With Conventional Invasive Coronary Angiography

Investigator (Ref)	Patients	Sensitivity (%)	Specificity (%)	Spatial Resolution (mm)	Temporal Resolution (ms)
Post (90)	20	38	95	$1.2 \times 2.3 \times 2.1$	260
Woodard (91)	10	70	–	$1.2 \times 2.0 \times 3.0$	–
Kessler (92)	73	65	88	$1.2 \times 1.2 \times 2.0$	125
Müller (93)	30	83	94	$1.2 \times 1.2 \times 2.0$	125
Sandstede (94)	30	81	89	$1.2 \times 1.2 \times 2.0$	230
van Geuns (117)	27	54	91	$1.95 \times 1.25 \times 2.0$	–
Regenfus (116)	50	94	57	$1.4 \times 1.25 \times 1.5$	294
van Geuns (101)	38	68	97	$1.9 \times 1.25 \times 1.5$	–
Kim (104)	109	93	42	–	–
Total	387	77	71	–	–

**Table 6.** Strengths and Weaknesses of Each of the Three Noninvasive Angiography Techniques

Electron Beam Angiography	Multislice Computed Tomography	Magnetic Resonance Angiography
<b>FDA approved</b> Limited availability	Not FDA approved <b>Equipment widely available</b>	Not FDA approved <b>Equipment widely available</b>
<b>Standardized protocol</b> Requires iodinated contrast and radiation	Protocols under development Requires iodinated contrast and radiation	Protocols under development <b>No iodinated contrast or radiation required</b>
<b>Multiple studies reported</b>	Limited studies reported	<b>Multiple studies reported</b>
<b>Consistent results across different laboratories</b>	Limited experience	Varied results in different laboratories

Bold terms demonstrate relative strength.  
FDA = Food and Drug Administration.

not an alternative to conventional CCA in all cases (Table 6). All three, however, are currently used clinically in certain centers. Selective use might prove both cost-effective and provide a safer, less-invasive method for patients. These noninvasive techniques have potential capabilities of assessing perfusion and coronary flow in addition to coronary anatomy, and thus may provide a comprehensive cardiac evaluation.

Successful development of a noninvasive angiogram with consistently high sensitivity and specificity for obstructive CAD would greatly reduce the cost and also the morbidity and mortality currently associated with conventional coronary arteriography. The replacement of some of these invasive procedures by noninvasive means would be very desirable. Some potential uses include: following the non-diagnostic stress test; for those persons with intermediate likelihood of CAD (where the step to coronary angiography might be premature); for symptomatic persons postcoronary angioplasty and possibly post-stent; evaluating graft patency post-CABG, and for early detection of obstructive CAD in the high-risk individual. Given the current utility of these techniques, we can expect a rapid growth in both the knowledge and experience with noninvasive angiography, leading to a much wider clinical use of these new techniques in visualizing the coronary lumens to evaluate obstructive coronary disease.

**Reprint requests and correspondence:** Dr. Matthew J. Budoff, Harbor-UCLA Research and Education Institute, 1124 W. Carson Street, RB2, Torrance, California 90502. E-mail: Budoff@flash.net.

## REFERENCES

- Marcus ML, Schelbert HR, Skorton DJ, et al., editors. Cardiac Imaging: A Companion to Braunwald's Heart Disease. Philadelphia, PA: Saunders, 1991.
- Scanlon PJ, Faxon DP, Audet AM, et al. ACC/AHA guidelines for coronary angiography. A report of the American College of Cardiology/American Heart Association Task Force on practice guidelines (Committee on Coronary Angiography). Developed in collaboration with the Society for Cardiac Angiography and Interventions. J Am Coll Cardiol 1999;33:1756-824.
- American Heart Association. Heart and stroke facts: 2003 Statistical supplement. Dallas, TX: American Heart Association, 2003;1-46.
- 1992 Hospital charges for two major surgical procedures for cardiovascular diseases: II. cardiac catheterization. Stat Bull Metrop Insur Co 1994;75:21-8.
- Lee JC, Bengtson JR, Lipscomb J, et al. Feasibility and cost-saving potential of outpatient cardiac catheterization. J Am Coll Cardiol 1990;5:378-84.
- Agency for Healthcare Research and Quality, Healthcare Cost and Utilization Project, HCUPnet, Washington, DC, 2000.
- Hanley PC, Vlietstra RE, Fisher LD, et al. Indications for coronary angiography: changes in laboratory practice over a decade. Mayo Clin Proc 1986;61:248-53.
- Emond M, Mock MB, Davis KB, et al. Long-term survival of medically treated patients in the Coronary Artery Surgery Study (CASS) registry. Circulation 1994;90:2645-57.
- Johnson LW, Lozner EC, Johnson S, et al. Coronary arteriography 1984-1987: a report of the registry of the Society for Cardiac Angiography and Intervention. Cathet Cardiovasc Diagn 1989;17:5-10.
- Kugelmass AD, Houser F, Simon AW, et al. Diagnostic results: gender continues to make a difference. J Am Coll Cardiol 2001;37:497A.
- Tanenbaum SR, Kondos GT, Veselik KE, et al. Detection of calcific deposits in coronary arteries by ultrafast computed tomography and correlation with angiography. Am J Cardiol 1989;63:870-2.
- Agatston AS, Janowitz WR, Hildner FJ, et al. Quantification of coronary artery calcium using ultrafast computed tomography. J Am Coll Cardiol 1990;15:827-32.
- Wexler L, Brundage B, Crouse J, et al. Coronary artery calcification: pathophysiology, epidemiology, imaging methods, and clinical implications. A statement for health professionals. From the American Heart Association. Circulation 1996;94:1175-92.
- Breen JF, Sheedy PF, Schwartz RS, et al. Coronary artery calcification detected with ultrafast CT as an indication of coronary artery disease. Radiology 1992;185:435-9.
- Agatston AS, Janowitz WR, Kaplan G, et al. Ultrafast computed tomography detected coronary calcium reflects the angiography extent of coronary arterial atherosclerosis. Am J Cardiol 1994;74:1272-4.
- Arad Y, Sparado LA, Goodman K, et al. Prediction of coronary events with electron beam computed tomography. J Am Coll Cardiol 2000;36:1253-60.
- Raggi P, Callister TQ, Cooil B, et al. Identification of patients at increased risk of first unheralded acute myocardial infarction by electron beam computed tomography. Circulation 2000;101:850-5.
- Mautner SL, Mautner GC, Froenlich J, et al. Coronary artery calcification assessment with electron beam CT and histomorphometric correlation. Radiology 1994;192:619-23.
- Budoff MJ. Atherosclerosis imaging and calcified plaque: coronary artery disease risk assessment. Prog Cardiovasc Dis 2003;46:135-48.
- Thomas PJ, McCollough CH, Ritman EL. An electron-beam CT approach for transvenous coronary arteriography. J Comput Assist Tomogr 1995;19:383-9.
- Uchino A, Kato A, Kudo S. CT angiography using electron-beam computed tomography (EBCT): phantom study. Radiat Med 1997;15:272-6.
- Moshage WE, Achenbach S, Seese B, et al. Coronary artery stenosis: three-dimensional imaging with electrocardiographically triggered, contrast agent enhanced, electron-beam CT. Radiology 1995;196:707-14.
- Nakanishi T, Ito K, Imazu M, et al. Evaluation of coronary artery stenoses using electron beam CT and multiplanar reformation. J Comput Assist Tomogr 1997;21:121-7.
- Achenbach S, Moshage W, Ropers D, et al. Curved multiplanar reconstructions for the evaluation of contrast-enhanced electron beam CT of the coronary arteries. AJR Am J Roentgenol 1998;170:895-9.
- Reddy GP, Chernoff DM, Adams JR, et al. Coronary artery stenoses: assessment with contrast-enhanced electron-beam CT and axial reconstructions. Radiology 1998;208:167-72.

26. Budoff MJ, Oudiz RJ, Zalace CP, et al. Intravenous three-dimensional coronary angiography using contrast-enhanced electron beam computed tomography. *Am J Cardiol* 1999;83:840-5.
27. Achenbach S, Moshage W, Ropers D, et al. Value of electron-beam-computed tomography for the noninvasive detection of high-grade coronary artery stenoses and occlusions. *N Engl J Med* 1998;339:1964-71.
28. Chernoff DM, Ritchie CJ, Higgins CB, et al. Evaluation of electron beam CT coronary angiography in healthy subjects. *AJR Am J Roentgenol* 1997;169:93-9.
29. Achenbach S, Moshage W, Ropers D, et al. Comparison of vessel diameters in electron beam tomography and quantitative coronary angiography. *Int J Card Imaging* 1998;14:1-7.
30. Rensing BJ, Bongaerts A, Van Geuns RJ, et al. Intravenous coronary angiography by electron beam computed tomography: a clinical evaluation. *Circulation* 1998;98:2509-12.
31. Schmermund A, Rensing B, Sheedy P, et al. Intravenous electron-beam computed tomography coronary angiography for segmental analysis of coronary artery stenosis. *J Am Coll Cardiol* 1998;31:1547-54.
32. Mao SS, Lu B, Oudiz RJ, et al. Coronary artery motion in electron beam tomography. *J Comput Assist Tomogr* 2000;24:253-8.
33. Achenbach S, Ropers D, Holle J, et al. In-plane coronary arterial motion velocity: measurement with electron-beam CT. *Radiology* 2000;216:457-63.
34. McCollough CH, Daly TR. Performance evaluation of electron beam CT scanners: comparison of various hardware and software configurations. *Am J Card Imaging* 1996;10 Suppl 1:10-7.
35. Achenbach S, Moshage W, Ropers D. Noninvasive, three-dimensional visualization of coronary artery bypass grafts by electron beam tomography. *Am J Cardiol* 1997;79:856-61.
36. Bateman TM, Gray RJ, Whiting JS, et al. Cine computed tomographic evaluation of aortocoronary bypass graft patency. *J Am Coll Cardiol* 1986;8:693-8.
37. Bateman TM, Gray RJ, Whiting JS, et al. Prospective evaluation of ultrafast cardiac computed tomography for determination of coronary bypass graft patency. *Circulation* 1987;75:1018-24.
38. Stanford W, Krachmer M, Galvin JR. Ultrafast computed tomography in assessing coronary bypass grafts. *Am J Card Imaging* 1991;5:21-8.
39. McKay CR, Brundage BH, Ulyot DJ, et al. Evaluation of early postoperative coronary artery bypass grafts patency by contrast-enhanced computed tomography. *J Am Coll Cardiol* 1983;2:312-7.
40. Dai R, Zhang S, Lu B, et al. Electron beam CT angiography with three-dimensional reconstruction in the evaluation of coronary artery bypass grafts. *Acad Radiol* 1998;5:863-7.
41. Ha JW, Cho SY, Shim WH, et al. Noninvasive evaluation of coronary artery bypass graft patency using three-dimensional angiography obtained with contrast-enhanced electron beam CT. *AJR Am J Roentgenol* 1999;172:1055-9.
42. Lu B, Dai RP, Jing BL, et al. Evaluation of coronary artery bypass graft patency using three-dimensional reconstruction and flow study on electron beam tomography. *J Comput Assist Tomogr* 2000;24:663-70.
43. Vandormael MG, Deligonul U, Kern MJ. Multilesion coronary angioplasty: clinical and angiographic follow-up. *J Am Coll Cardiol* 1987;10:246-52.
44. Achenbach S, Moshage W, Bachmann K. Detection of high-grade restenosis after PTCA using contrast-enhanced electron beam CT. *Circulation* 1997;96:2785-8.
45. Serruys PW, Strauss BH, Beatt KJ, et al. Angiographic follow-up after placement of a self-expanding coronary artery stent. *N Engl J Med* 1991;324:13-7.
46. Steffenino G, Mejer B, Finci L, et al. Acute complications of selective coronary angioplasty: preview of 500 consecutive procedures. *Br Heart J* 1988;59:151-8.
47. Pump H, Moehlenkamp S, Sehnert C, et al. Electron-beam CT in the noninvasive assessment of coronary stent patency. *Acad Radiol* 1998;5:858-62.
48. Schmermund A, Haude M, Baumgart D, et al. Noninvasive assessment of coronary Palmaz-Schatz stents by contrast enhanced electron beam computed tomography. *Eur Heart J* 1996;17:1546-53.
49. Lu B, Dai RP, Bai H, et al. Detection and analysis of intracoronary artery stent after PTCA using contrast-enhanced three-dimensional electron beam tomography. *J Invasive Cardiol* 2000;12:1-6.
50. Pump H, Mohlenkamp S, Sehnert CA, et al. Coronary arterial stent patency: assessment with electron-beam CT. *Radiology* 2000;214:447-52.
51. Ropers D, Moshage W, Daniel WG, et al. Visualization of coronary artery anomalies and their anatomic course by contrast-enhanced electron-beam tomography and 3-dimensional reconstruction. *Am J Cardiol* 2001;87:193-7.
52. Baik HK, Budoff MJ, Lane KL, et al. Accurate measures of ejection fraction using electron beam tomography, radionuclide angiography, and catheterization angiography. *Int J Card Imaging* 2000;16:391-8.
53. Budoff MJ, Brundage BH. Newer imaging modalities: electron beam computed tomography. In: Willerson JT, Cohn JN, editors. *Cardiovascular Medicine*. 2nd ed. Philadelphia, PA: Saunders, 2000: Chap. 21, 571-606.
54. Becker C, Schatzl M, Feist H, et al. Assessment of the effective dose for routine protocols in conventional CT, electron beam CT and coronary angiography. *Rofo Fortschr Geb Rontgenstr Neuen Bildgeb Verfahr* 1999;170:99-104.
55. Lu B, Mao SS, Zhuang N, et al. Coronary artery motion during the cardiac cycle and optimal ECG triggering for coronary artery imaging. *Invest Radiol* 2001;36:250-6.
56. Achenbach S, Ulzheimer S, Baum U, et al. Non-invasive coronary angiography by retrospectively ECG-gated multislice spiral CT. *Circulation* 2000;102:2823-8.
57. Achenbach S, Geisler T, Ropers D, et al. Comparison of image quality in contrast-enhanced coronary artery visualization by electron beam tomography and retrospectively electrocardiogram-gated multislice spiral computed tomography. *Invest Radiol* 2003;38:119-28.
58. Knez A, Leber A, Becker CR, et al. Multislice-detector-helical computed tomography for non-invasive angiography: a new imaging modality for determination of severe coronary artery disease (abstr). *Circulation* 2000;102:II411.
59. Achenbach S, Giesler T, Ropers D, et al. Detection of coronary artery stenoses by contrast-enhanced, retrospectively electrocardiographically-gated, multislice computed tomography. *Circulation* 2001;103:2535-8.
60. Giesler T, Baum U, Ropers D, et al. Noninvasive visualization of coronary arteries using contrast-enhanced multidetector CT: influence of heart rate on image quality and stenosis detection. *AJR Am J Roentgenol* 2002;179:911-6.
61. Nieman K, Rensing BJ, van Geuns RJ, et al. Non-invasive coronary angiography with multislice computed tomography: impact of heart rate. *Heart* 2002;88:470-4.
62. Nieman K, Rensing BJ, van Geuns RJ, et al. Usefulness of multislice computed tomography for detecting obstructive coronary artery disease. *Am J Cardiol* 2002;89:913-8.
63. Kuettner A, Kopp AF, Schroeder S, et al. Diagnostic accuracy of MDCT-coronary-angiography in patients with angiographically proven coronary artery disease. *J Am Coll Cardiol* 2003. In Press.
64. Knollmann FD, Hidajat N, Felix R. CTA of the coronary arteries: comparison of radiation exposure with EBCT and multi-slice detector CT. *Radiology* 2000;217:364-5.
65. International Commission on Radiological Protection. *Recommendation of the ICRP*. ICRP Publication 60. Oxford, UK: Pergamon Press, 1990.
66. Hunold P, Vogt FM, Schmermund A, et al. Radiation exposure during cardiac CT: effective doses at multi-detector row CT and electron-beam CT. *Radiology* 2003;226:145-52.
67. Morin RL, Gerber TC, McCollough CH. Radiation dose in computed tomography of the heart. *Circulation* 2003;107:917-22.
68. Ropers D, Baum U, Pohle K, et al. Detection of coronary artery stenosis with thin-slice multi-detector row spiral computed tomography and multiplanar reconstruction. *Circulation* 2003;107:664-6.
69. Nieman K, Cademartiri F, Lemos PA, et al. Reliable noninvasive coronary angiography with fast submillimeter multislice computed tomography. *Circulation* 2002;106:2051-4.
70. Duerinckx AJ. Imaging of coronary artery disease—MR. *J Thorac Imaging* 2001;16:25-34.
71. Duerinckx AJ. Coronary MR angiography. *Radiol Clin North Am* 1999;37:273-318.
72. Anderson CM, Edelman RR, Turski PA. *Clinical Magnetic Resonance Angiography*. New York, NY: Raven Publishers, 1993.

73. Duerinckx AJ, Urman MK. Two-dimensional coronary MR angiography: analysis of initial clinical results. *Radiology* 1994;193:731-8.
74. Wielopolski PA, van Geuns RJ, de Feyter PJ, et al. Coronary arteries. *Eur Radiol* 2000;10:12-35.
75. Fayad ZA, Fuster V, Fallon JT, et al. Noninvasive in vivo human coronary artery lumen and wall imaging using black-blood magnetic resonance imaging. *Circulation* 2000;102:506-10.
76. Botnar RM, Stuber M, Kissinger KV, et al. Noninvasive coronary vessel wall and plaque imaging with magnetic resonance imaging. *Circulation* 2000;102:2582-7.
77. Edelmann RR, Manning WJ, Burnstein D, et al. Coronary arteries: breath-hold MR angiography. *Radiology* 1990;181:641-3.
78. Manning WJ, Li W, Edelman RR. A preliminary report comparing magnetic resonance coronary angiography with conventional angiography. *N Engl J Med* 1993;328:828-32.
79. Duerinckx AJ, Atkinson DP, Mintonovitch J, et al. Two-dimensional coronary MRA: limitations and artifacts. *Eur Radiol* 1996;6:312-25.
80. Pennel DJ, Bogren HG, Keegan J, et al. Assessment of coronary artery stenosis by magnetic resonance imaging. *Heart* 1996;75:127-33.
81. Post JC, van Rossum AC, Hofman MBM, et al. Clinical utility of two-dimensional magnetic resonance angiography in detecting coronary artery disease. *Eur Heart J* 1997;18:426-33.
82. Mohiaddin RH, Bogren HG, Lazim F, et al. Magnetic resonance coronary angiography in heart transplant recipients. *Coron Artery Dis* 1996;7:591-7.
83. Paschal CB, Haacke EM, Adler LP. Three-dimensional MR imaging of the coronary arteries: preliminary clinical experience. *J Magn Reson Imaging* 1993;3:491-500.
84. Li D, Paschal CB, Haacke EM, et al. Coronary arteries: three-dimensional MR imaging with fat saturation and magnetization transfer contrast. *Radiology* 1993;187:401-6.
85. Cline HE, Thedens DR, Irarrazaval P, et al. 3D MR coronary segmentation. *Magn Reson Med* 1998;40:697-702.
86. Hany TF, Schmidt M, Davis CP, et al. Diagnostic impact of four postprocessing techniques in evaluating contrast-enhanced three-dimensional MR angiography. *AJR Am J Roentgenol* 1998;170:907-12.
87. Post JC, van Rossum AC, Hofman MBM, et al. Protocol for two-dimensional magnetic resonance coronary angiography studied in three-dimensional magnetic resonance data sets. *Am Heart J* 1995;130:167-73.
88. Hofman MBM, Paschal CB, Li D, et al. MRI of coronary arteries: 2D breathhold versus 3D respiratory-gated acquisition. *J Comput Assist Tomogr* 1995;19:56-62.
89. Wang Y, Rossman PJ, Grimm RC, et al. Navigator-echo-based real-time respiratory gating and triggering for reduction of respiration effects in three-dimensional coronary MR angiography. *Radiology* 1996;198:55-60.
90. Post JC, van Rossum AC, Hofman MB, et al. Three-dimensional respiratory gated MR angiography of coronary arteries: comparison with conventional coronary angiography. *AJR Am J Roentgenol* 1996;166:1399-404.
91. Woodard PK, Li D, Haacke EM, et al. Detection of coronary stenoses on source and projection images using three-dimensional MR angiography with retrospective gating: preliminary experience. *AJR Am J Roentgenol* 1998;170:883-8.
92. Kessler W, Achenbach S, Moshage W, et al. Usefulness of respiratory gated magnetic resonance coronary angiography in assessing narrowings  $\geq 50\%$  in diameter in native coronary arteries and in aorto-coronary bypass conduits. *Am J Cardiol* 1997;80:989-93.
93. Müller MF, Fleisch M, Kroeker R, et al. Proximal coronary artery stenosis: three-dimensional MRI with fat saturation and navigator echo. *J Magn Reson Imaging* 1997;7:644-51.
94. Sandstede JJW, Pabst T, Beer M, et al. Three-dimensional angiography using the navigator technique compared with conventional coronary angiography. *AJR Am J Roentgenol* 1999;172:135-9.
95. Ropers D, Achenbach S, Birke S, et al. Noninvasive coronary angiography using contrast-enhanced magnetic resonance imaging and electron beam computed tomography: comparison of the contrast-to-noise ratio. *J Am Coll Cardiol* 2000;35 Suppl A:A15A.
96. Stuber M, Stuber M, Botnar RM, et al. Double-oblique free-breathing high resolution three-dimensional coronary magnetic resonance angiography. *J Am Coll Cardiol* 1999;34:524-31.
97. Danias PG, McConnell MV, Khasiwala VC, et al. Prospective navigator correction of image position for coronary MR angiography. *Radiology* 1997;203:733-6.
98. Oshinski JN, Hofland L, Dixon WT, et al. Magnetic resonance coronary angiography using respiratory gated real-time slice following. *Int J Card Imaging* 1998;14:191-9.
99. Goldfarb JW, Edelman R. Coronary arteries: breath-hold, gadolinium-enhanced, three-dimensional MR angiography. *Radiology* 1998;206:830-4.
100. Moshage W, Ropers D, Daniel WG, et al. Noninvasive imaging of coronary arteries with electron beam tomography. *Z Kardiol* 2000;89 Suppl 1:15-20.
101. van Geuns RJ, Wielopolski PA, de Bruin HG, et al. MR coronary angiography with breath-hold targeted volumes: preliminary clinical results. *Radiology* 2000;217:270-7.
102. Wielopolski PA, van Geuns RJ, de Feyter PJ, et al. Breath-hold coronary MR angiography with volume targeted imaging. *Radiology* 1998;209:209-19.
103. Kessler W, Laub G, Achenbach S, et al. Coronary arteries: MR angiography with fast contrast-enhanced three-dimensional breath-hold imaging—initial experience. *Radiology* 1999;210:566-72.
104. Kim WY, Danias PG, Stuber M, et al. Coronary magnetic resonance angiography for the detection of coronary stenoses. *N Engl J Med* 2001;345:1863-9.
105. Li D, Dolan RP, Walowitch RC, et al. Three-dimensional MRI of coronary arteries using an intravascular contrast agent. *Magn Reson Med* 1998;39:1014-8.
106. Hofman MBM, Henson RE, Kovács, et al. Blood pool agent strongly improves 3D magnetic resonance coronary angiography using an inversion pre-pulse. *Magn Reson Med* 1999;41:360-7.
107. Galjee MA, Van Rossum AC, Doesburg T, et al. Value of magnetic resonance imaging in assessing patency and function of coronary bypass grafts: an angiographically controlled study. *Circulation* 1996;93:660-6.
108. Vrachliotis TG, Bis KG, Aliabadi D, et al. Contrast-enhanced breath-hold MR angiography for evaluating patency of coronary artery bypass grafts. *AJR Am J Roentgenol* 1997;168:1073-80.
109. McConnell MV, Ganz P, Selwyn AP, et al. Identification of anomalous coronary arteries and their anatomic course by magnetic resonance coronary angiography. *Circulation* 1995;92:3158-62.
110. Post JC, van Rossum AC, Bronzwaer JGF, et al. Magnetic resonance angiography of anomalous coronary arteries. A new standard for delineating the proximal course? *Circulation* 1995;92:3163-71.
111. Nakanishi T, Ito K, Imazu M, et al. Evaluation of coronary artery stenoses using electron-beam and multiplanar reformations. *J Comput Assist Tomogr* 1997;21:121-7.
112. Achenbach S, Ropers D, Regenfus M, et al. Contrast-enhanced electron beam computed tomography to analyse the coronary arteries in patients after acute myocardial infarction. *Heart* 2000;84:489-93.
113. Lu B, Zhuang N, Mao SS, et al. Image quality of three-dimensional electron beam coronary angiography. *J Comput Assist Tomogr* 2002;26:202-9.
114. Hong C, Becker CR, Knez A, et al. Multislice CT coronary angiography for segmental analysis of coronary artery disease (abstr). *Radiology* 2000;217:374.
115. Giesler T, Ropers D, Baum U, et al. Contrast-enhanced retrospectively ECG-gated multislice spiral CT: detection of coronary stenoses (abstr). *Radiology* 2001;221:503-4.
116. Regenfus M, Ropers D, Achenbach S, et al. Noninvasive detection of coronary artery stenosis using contrast-enhanced three-dimensional breath-hold magnetic resonance coronary angiography. *J Am Coll Cardiol* 2000;36:44-50.
117. van Geuns RJ, Bongaerts AH, De Bruin HG, Rewnsing BJ, DeFiejer PJ, Oudkerk M. Noninvasive coronary imaging: a comparison between respiratory gated magnetic resonance imaging and electron beam computed tomography. *Eur Heart J* 1999;20:263-70.